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RESEARCH MEMORANDUM

SOME DESIGN AND OPERATIONAL CONSIDERATIONS OF A
LIQUID-HYDROGEN FUEL AND HEAT-SINK SYSTEM
FOR TURBOJET-ENGINE TESTS

By Lester C. Corrington, Kenneth L. Thornbury, and Glen Hennings

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SUMMARY

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An experimental investigation was conducted in which liquid hydrogen was used as a heat sink for turbine-cooling in a high-temperature turbojet engine. A production-model turbojet engine was modified by the installation of a cooled-turbine rotor and stator and was operated on hydrogen maintained in the supply tank as a liquid. The turbine cooling air was refrigerated by the cold hydrogen as it passed through a heat exchanger. Cooling-air temperatures of 160° to 220° R were obtained at the exit of the heat exchanger with cooling-air flow rates of 3 to 14 percent of the engine airflow.

A few problem areas were revealed which will require special attention in future work. A pressure-surfing condition in the fuel system was apparently caused by the vaporization process in the counter-flow-type air-fuel heat exchanger. Liquefaction of air in the heat exchanger necessitated a redesign of the airflow passages to provide for a re-evaporation of the liquid by the incoming air. Icing of the heat exchanger was not a problem for continuous runs up to 45 minutes when the incoming air was dried to a moisture content of 2 grains per pound. A fire at the hydrogen-tank vent outlet was apparently ignited by a static discharge or a frictional spark from the supporting cables, emphasizing the fact that great care must be used to prevent any undesired exposure of hydrogen to air.

Information on the properties of hydrogen is summarized as an aid in the design of systems to handle this fuel in the liquid or gaseous state.

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INTRODUCTION

The continuing requirements for increased range and altitude capabilities for military aircraft have created increasing interest in high-energy fuels. Usually such fuels that have high heats of combustion have high-reactivity rates in addition, making them also attractive from the

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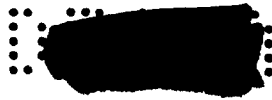
standpoint of combustion problems at high altitude. One such fuel that is currently receiving a great deal of attention is liquid hydrogen. This fuel, while having the disadvantage of low density, has a much higher heat of combustion than other high-energy fuels. An analysis of the potentialities of liquid hydrogen for increasing the range and altitude of several types of aircraft is presented in reference 1. In addition to showing the range and altitude advantages that this fuel promises, reference 1 points out that, because of its low boiling point and high specific heat, liquid hydrogen has good potentialities as a heat sink for cooling engine parts and aircraft surfaces in high-speed airplanes.

A specific application in which the cooling capabilities of liquid hydrogen can be used to advantage is in the cooling of turbines in high-temperature turbojet engines. The temperature of the turbine cooling air from a liquid-hydrogen heat exchanger would be much lower than the temperature of the air directly from the compressor, which should permit the operation of a cooled turbine at much higher gas temperatures than would otherwise be the case.

This heat-sink application has been investigated experimentally in an altitude test chamber at the NACA Lewis laboratory using a current-model turbojet engine modified to a cooled-turbine engine. The primary objective of this investigation is to determine the heat-transfer characteristics of the turbine blades with the low-temperature cooling air available from the hydrogen heat sink with high turbine gas temperatures and at high altitudes. Inasmuch as the experimental setup requires the use of a liquid-hydrogen fuel system including suitable tanks, plumbing, heat exchanger, flow control, and instrumentation, a secondary objective is to examine the problems that may exist in the use of such a system.

The experimental results regarding the heat-transfer characteristics of the turbine blades are presented in reference 2. A discussion of the problems involved in the modification of the current turbojet engine used in this investigation to a cooled-turbine engine with high turbine-inlet temperatures is presented in reference 3.

This report presents a description of the fuel and cooling-air systems used in this investigation, and a discussion of the operational procedures used and the problems encountered in using these systems for turbine-cooling purposes. The properties of hydrogen pertinent to fuel-system design are discussed in the appendix, because such information has not been available heretofore in a form convenient for engineering purposes.

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FUEL SYSTEM


The fuel system used in this investigation is illustrated diagrammatically in figure 1. All parts of the system upstream of the shutoff valve were located outside the test chamber building for safety reasons. Figure 2 shows the physical arrangement of most of the system.

The fuel tanks were tactical Dewars of about 125-pound capacity each. These Dewars were of triple wall construction. The innermost wall was made of stainless steel and formed the pressure vessel for the fuel. This wall was surrounded completely by a second wall which served as a radiation shield. The radiation shield was made with an integral container which could be filled with a low-temperature liquid such as liquid nitrogen. Through thermal conduction the entire radiation shield wall would come to a temperature near that of the liquid in the container. This wall was in turn surrounded by reflective insulation and a vacuum-tight outer jacket. The spaces between the outer jacket and inner wall were evacuated.

These fuel tanks were filled from a large refrigerated Dewar mounted on a transport trailer bed. The tanks were vented to the atmosphere until time for engine operation, at which time they were pressurized to about 60 pounds per square inch gage with gaseous hydrogen. Helium was not used for the pressurizing fluid because of its unknown solubility in liquid hydrogen. Since that time, however, the solubility of helium in liquid hydrogen has been found to be very small under these operating conditions.

The pressurized liquid flowed to the air-fuel heat exchanger through double-walled vacuum-insulated lines. These lines were made with an inner wall of stainless-steel tubing of about 5/8-inch inside diameter and an outer wall of copper. A high vacuum was maintained between these walls.

The air-fuel heat exchanger was of the counter-flow type made from two commercially available cores of aluminum-finned copper tubing enclosed in a heavy outer shell. An external view of the heat exchanger is shown in figure 3, and a cross-sectional diagram in figure 4. The fuel entered at the left (fig. 4) and flowed alternately upward and downward through a number of tubes connected in parallel and provided with flow distribution manifolds as indicated. The turbine cooling air entered a plenum chamber at the right, passed through both cores, made a 90° turn, and passed out in an upward direction. The cross-sectional area of the core at the fuel-entrance end of the heat exchanger is smaller than that of the other core because at this point both the fuel and air densities are much higher (lower temperature) than at the other end of the heat exchanger.



All parts of the heat exchanger except the heavy outer shell, the air-inlet pipe, and the core were made of stainless steel because of its good low-temperature ductility characteristics. The outer shell and air-inlet pipe were mild steel.

The gaseous hydrogen from the heat exchanger passed through a steam heater with an automatic temperature control to heat it to about 75° F to ease the handling and flow-measurement problems. Flow measurement and control at low temperatures are difficult because of the large variations in the specific heat ratio with temperature, pressure, and fuel composition (see appendix).

The fuel then passed through a 2-inch line to a high-response-rate pressure control, a volume chamber, a flow-measuring orifice, a remotely controlled throttling valve (see fig. 5), a positive shutoff valve, and the engine manifold. The high-response-rate pressure control and the volume chamber were necessitated by pressure fluctuations in the system and are discussed further in the section OPERATIONAL CHARACTERISTICS OF SYSTEMS.

TURBINE COOLING-AIR SYSTEM

A schematic diagram of the turbine cooling-air system is shown in figure 6, and part of the system appears in figure 3. The cooling air for the turbine stator was taken directly from the laboratory supply, while that for the turbine rotor was refrigerated in the air-fuel heat exchanger.

The supply air was dried to a moisture content of about 2 grains per pound or less to prevent excessive icing in the heat exchanger. In a standard atmosphere above an altitude of 25,000 feet saturated air has a moisture content less than 2 grains per pound.

The temperature and flow rate of the turbine-rotor cooling air were controlled manually by bypassing some of the air around the heat exchanger and bleeding off refrigerated air downstream of the heat exchanger. Flow rates were measured in straight sections of pipe using total-pressure surveys, wall static pressures, and thermocouple readings at the flow measuring stations.

The refrigerated air line downstream of the heat exchanger was made of stainless steel and was heavily insulated to keep the air temperature as low as possible at the entrance to the turbine. This line was quite long because of the outdoor location of the heat exchanger.

ENGINE AND INSTALLATION

The cooled-turbine engine used in this investigation is described in detail in references 2 and 3. It consisted of an axial-flow turbojet engine which was altered to include an air-cooled turbine rotor bladed with noncritical materials and an air-cooled stator made of a high-temperature alloy, N-155. The rotor cooling air entered the engine through two tailcone struts. It then passed forward through an axial duct into the hollow turbine wheel and out through the hollow corrugated-insert-type rotor blades. The stator cooling air entered the engine through eight small ducts and passed radially outward through the hollow corrugated-insert-type stator blades. Additional cooling for the sheet-metal parts in the turbine region was provided for by enlarging the cooling-air passages surrounding the combustor transition liners. The fuel nozzles were essentially open tubes with slotted caps on the end as shown in figure 7.

The engine was installed in an altitude test chamber to permit operation at high altitudes and, consequently, low fuel flows. This was necessary because of the limited fuel supply and small fuel-tank capacity. The installation is shown in figures 8 and 9.

Fuel was piped to the engine through a manifold made of 3-inch tubing and through eight 1-inch lines to the eight fuel nozzles. Instrumentation was provided to measure gas temperatures and pressures throughout the engine and metal temperatures in the turbine section, including the rotor blades and the turbine disk. Details of this instrumentation are presented in references 2 and 3.

OPERATIONAL PROCEDURE

Preparation of Fuel System

Before being filled with liquid hydrogen the fuel tanks (tactical Dewars) were precooled by filling the radiation shield containers with liquid nitrogen several days in advance of their initial use. These radiation shield containers were then kept filled continuously throughout the investigation.

Air was removed from the fuel system to eliminate any possibility of an explosive mixture in the system and to prevent any trouble with frozen air at the liquid-hydrogen temperatures. This was done by three successive evacuation and helium-filling cycles. After the third filling the valves at the tank outlets were closed and helium was trapped in the downstream system at a pressure of about 20 pounds per square inch gage.

The tanks were then connected to the trailer-mounted supply Dewar and the fuel transfer lines were inerted in a similar manner. The supply Dewar was then pressurized with gaseous hydrogen, the vent lines were opened to atmosphere, and the transferring operation was begun. Each tank was filled until a high rate of liquid-air formation at the vent connection indicated the presence of liquid hydrogen near the vent at this point. The vent lines were left open to atmosphere until the engine was to be started. They were then closed and the tanks were pressurized to about 60 pounds per square inch gage with gaseous hydrogen.

Operation of Engine and Shutdown of System

Because of the restricted fuel-tank capacity, operation of the engine was limited to periods of up to 45 minutes. In each case the engine was started on hydrogen and brought up to test conditions as quickly as possible. Fuel was used from each tank until the fuel flow began to drop off, indicating the passage of gas through the small-diameter liquid lines and its accompanying higher pressure drop. In each case it was possible to change to the next tank with the engine in continuous operation, so that test conditions could be quickly re-established. When the last tank of fuel had been used, the tank was quickly shut off and the lines from the tanks to the engine and the engine fuel system were purged with helium. The farthest downstream valve was then closed, and the helium was trapped in the system at a pressure of about 20 pounds per square inch gage until the next period of operation. The Dewars remained full of hydrogen gas at this same pressure between operating periods.

OPERATIONAL CHARACTERISTICS OF SYSTEMS

Fuel System

Initial operation of the engine disclosed a pressure-surging condition in the fuel system which made control of the engine unsatisfactory. This surging had an amplitude of several pounds per square inch and was erratic in nature, with a period varying from 2 to 5 seconds. The vaporization process in the heat exchanger appeared to be primarily responsible for the surging, and because time was not available for a heat-exchanger development program, an attempt was made to damp the system.

A 30-gallon volume chamber was installed (fig. 5) but did not improve the surging condition appreciably. A high-response-rate pressure control was then installed, and this control in combination with the volume chamber provided a steady downstream pressure over the required flow range of 100 to 650 pounds per hour.

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This pressure control consisted of a servo-actuated valve and pressure sensing system capable of attenuating pressure fluctuations up to 10 cycles per second, and the previously mentioned volume chamber just downstream of the valve which removed pressure fluctuations above 10 cycles per second. The valve, servomotor, and pressure sensing components are commercially available items. The electronic control circuit was built at the Lewis laboratory and provided proportional-plus-integral-type control.

As noted in the description of the fuel system, a venting system was used to dissipate boil-off fuel from the tanks to atmosphere. The vent outlet was initially located as shown in figure 2. However, because the gas was being vented at low temperature, its density was relatively high and did not dissipate into the atmosphere as rapidly as expected. For safety reasons the vent outlet was subsequently raised to about 25 feet above the building.


On one occasion when hydrogen was being vented, it caught fire at the vent outlet. No ignition sources were apparent, so it must be assumed that the ignition was caused by a static discharge or frictional spark from the supporting cables. While this did no harm, it emphasizes the fact that hydrogen must be handled very carefully to prevent any undesired exposure to air.

Turbine Cooling-Air System

Quantitative data for determining the effectiveness of the heat exchanger were not obtained. Air temperatures at the heat-exchanger outlet of about 160° to 220° R were measured along with hydrogen-gas temperatures at the heat-exchanger outlet of 200° to 270° R depending on operating conditions. These air temperatures were obtained with airflow rates of 3 to 14 percent of the engine airflow. Because of heat leakage in the long line between the heat exchanger and the engine, and in the passages through the tailcone, the minimum air temperature delivered to the hollow turbine wheel was about 290° R. The minimum air temperature delivered to the turbine blades was about 390° R because of the temperature rise in passing through the wheel.

The main problem encountered in the turbine cooling-air system was the formation of liquid air in the heat exchanger. With the heat exchanger as it was originally built, this liquid air flowed into the inlet end of the outer shell and caused numerous cracks in the mild steel material. Operation of the system was stopped before the level of liquid air was high enough to immerse an appreciable part of the core.

The boiling and freezing points of oxygen and nitrogen are shown in figure 10. As indicated earlier, the minimum air temperature at the exit of the heat exchanger was about 160° R. The pressure in the cooling-air



system varied from about 0.3 to 0.8 atmosphere at the heat exchanger, so that the air temperature was near the boiling temperature of oxygen. Condensation took place in the heat exchanger probably for the most part in the low-velocity regions around the tubing return bends (see fig. 4).

Sheet-metal additions were made to the inlet end of the heat exchanger to provide for evaporation of this liquid air by contact with the incoming warm air (see fig. 4) and to prevent its contact with the mild steel outer shell. In addition, a drain with an internal standpipe was provided to ensure against accumulation in the heat-exchanger core. After these alterations were made, no further difficulty was experienced with accumulations of liquid air.

It is not known whether there was any freezing of air on the heat-exchanger surfaces, but the cooling ability of the heat exchanger did not appear to be impaired at any time during continuous runs of up to 45 minutes. This also indicates that the moisture content of the incoming air (below 2 grain/lb) was low enough to avoid any serious icing problems in the heat exchanger for runs of this duration at airflow rates averaging about 1.0 pound per second.

SUMMARY OF RESULTS

The results of an experimental investigation in which liquid hydrogen was used as a heat sink for turbine-cooling and then used as a gas for turbojet-engine fuel are summarized as follows:

1. The use of liquid hydrogen as a heat sink for turbine-cooling provided cooling-air temperatures of 160° to 220° R at the exit of the heat exchanger with cooling-air flow rates of 3 to 14 percent of the engine airflow.

2. Pressure surging in the fuel system presented a problem in flow measurement and control. This surging apparently was caused by the vaporization process in the heat exchanger. The pressure surges were eliminated in the downstream portion of the system by the installation of a high-response-rate pressure control valve.


3. Dead air spaces in the heat exchanger can cause condensation of air. This condensation can possibly be eliminated by the provision of suitable air velocities past all hydrogen-cooled surfaces.

4. The air supplied to the heat exchanger was dried to a moisture content of about 2 grains per pound. This moisture content was low enough to prevent any serious accumulations of ice in the heat exchanger during runs of up to 45 minutes with average airflow rates of about 1.0 pound per second.

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5. At one time during low-rate venting from the fuel system the vent caught fire spontaneously, possibly from a static discharge or frictional spark from the supporting cables at the vent exit. This emphasizes the fact that hydrogen must be handled very carefully, especially when there is a possibility of undesired exposure to air.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 23, 1956



APPENDIX - PROPERTIES OF HYDROGEN

Lower Heat of Combustion

The lower heat of combustion for hydrogen is 51,571 Btu per pound. This compares with an average value for JP-4 fuel of 18,700 Btu per pound, or a ratio of 2.76.

Para- and Ortho-Hydrogen

Hydrogen exists in two well-defined energy states, para-hydrogen and ortho-hydrogen, the difference being associated with their nuclear spins. Both of these types are usually present as a mixture, the proportions of each depending on temperature and time. At room temperature the equilibrium proportions are 25 percent para-hydrogen and 75 percent ortho-hydrogen, while at the normal boiling point (36.5° R) the equilibrium mixture contains 99.8 percent para-hydrogen.

The conversion of hydrogen from one of these states to the other is a slow process and is accompanied by the liberation or absorption of heat. If hydrogen is liquified without catalysts after storage of the gas at room temperature, the mixture will be 25 percent para-hydrogen and 75 percent ortho-hydrogen. The ortho-hydrogen will then convert to the para- state with the liberation of 302 Btu per pound of ortho-hydrogen. The heat released by the conversion process, if it goes to completion, would be enough to vaporize about two-thirds of the liquid.

The approximate rate at which this conversion takes place is shown in figure 11. If the liquid is stored as long as 100 hours, the para-hydrogen concentration will increase to about 59 percent, and the heat release will be enough to vaporize about 40 percent of the mixture. Obviously, then, to prevent excessive loss either refrigeration must be provided during storage, or a catalytic process must be used in the liquefaction of hydrogen so that the conversion will take place during this process.

Since the fuel will probably be mostly para-hydrogen in fuel systems in which hydrogen is handled as a liquid, the properties of the para-state are of most interest. However, in many cases this information is not available, so in the figures that follow, the properties of para-hydrogen are presented where available, and the properties of "normal" hydrogen (25 percent para-, 75 percent ortho-) are presented where data for para-hydrogen are not available.



Vapor Pressure

The vapor pressure of hydrogen as a function of temperature is shown in figure 12. The normal boiling point (1-atm pressure) for para-hydrogen is 36.5°R . As the pressure is increased, the boiling temperature increases until the critical point is reached at a pressure of 12.8 atmospheres and a temperature of 59.8°R . At temperatures above the critical point, hydrogen cannot be a liquid regardless of pressure.

The triple point shown in figure 12 at 24.9°R represents the temperature below which hydrogen cannot exist as a liquid, but goes directly from the gaseous state to the solid state. The freezing line indicates a freezing point of about 25.2°R at atmosphere pressure for normal hydrogen. The freezing line for para-hydrogen would probably be only slightly different.

Density

Figure 13 shows the density of liquid hydrogen as a function of temperature. While the complete curve shown is for normal hydrogen, the curve for para-hydrogen would be only slightly displaced as indicated. This curve is interesting in that it indicates a rather large effect of pressure on the density of hydrogen stored at the boiling point. At sea-level atmospheric pressure, the density is about 4.41 pounds per cubic foot at the boiling point, while at a pressure of 4 atmospheres the density decreases to about 3.93 pounds per cubic foot at the boiling point. Thus, if tanks containing liquid hydrogen at the boiling point are to be pressurized to 4 atmospheres, the tankage volume must be increased by about 12 percent over that required at atmospheric pressure.

The density of gaseous hydrogen is shown in figure 14. Here again, the data shown are for normal hydrogen but are probably sufficiently accurate for most engineering purposes for para-hydrogen. The density at standard sea-level conditions (519°R , 1-atm pressure) is about 0.0053 pound per cubic foot.

Heat of Vaporization

The heat of vaporization of hydrogen is shown in figure 15 as a function of temperature. At the normal boiling point, the heat of vaporization for para-hydrogen is about 188 Btu per pound. As the temperature is increased, this value decreases until it reaches zero at the critical temperature of 59.8°R .



Specific Heat

Figure 16(a) shows the specific heat at constant pressure of gaseous hydrogen as a function of temperature and pressure. Data for para-hydrogen are available for only atmospheric pressure. These curves indicate a rather large effect of temperature on specific heat and a large difference between the specific heats of para- and normal hydrogen. The level of values for specific heat is very high as compared with most common fluids, and this fact plus the low boiling point makes hydrogen very attractive for heat-sink applications.

The specific heats of liquid and solid hydrogen are shown in figure 16(b).

The ratio of specific heats is shown in figure 17 as a function of temperature and pressure. Because of the large variation of the ratio of specific heats with both temperature and pressure in the low temperature range, slight variations in either in a fuel system would make large changes in the flow characteristics. Thus, flow measurement and flow control in fuel systems become very difficult problems at low temperatures.

Also significant is the large variation in the ratio of specific heats with fuel composition. Accurate flow measurements would require accurate knowledge of the percentages of para- and ortho-hydrogen in the mixture.


Enthalpy

Figure 18 is an enthalpy chart for hydrogen as a function of temperature and pressure. The difference between normal and para-hydrogen is the heat of conversion, 226.5 Btu per pound at the boiling point and near zero at room temperature.

Sound Velocity

The velocity of sound in hydrogen is shown as a function of temperature and pressure in figure 19. The data shown are for normal hydrogen, as data for para-hydrogen are not readily available. The velocity of sound is an important characteristic from the standpoint of pipe sizes in fuel systems.

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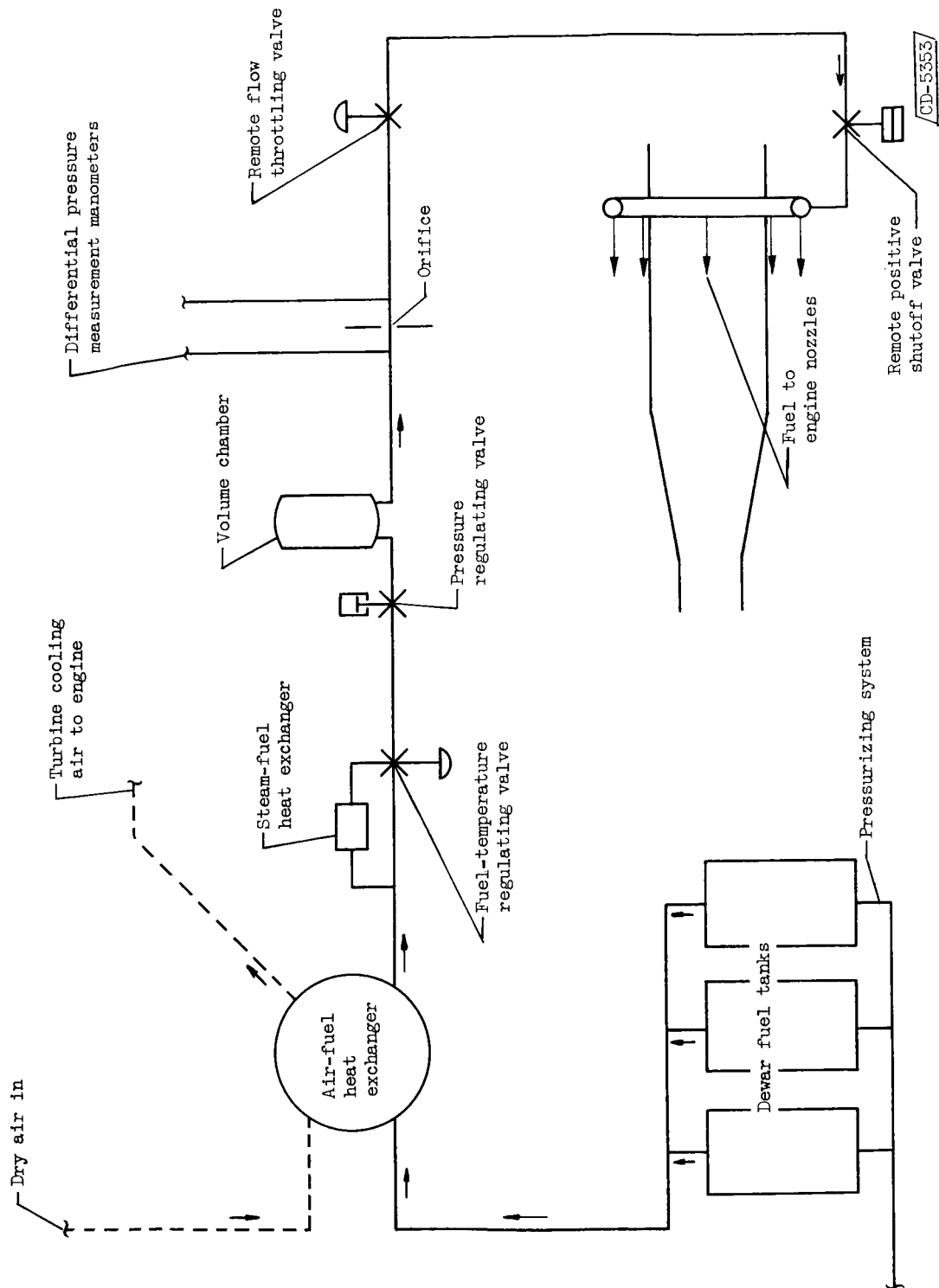


Figure 1. - Schematic diagram of fuel system.

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Figure 2. - Fuel supply tanks (tactical Dewars).

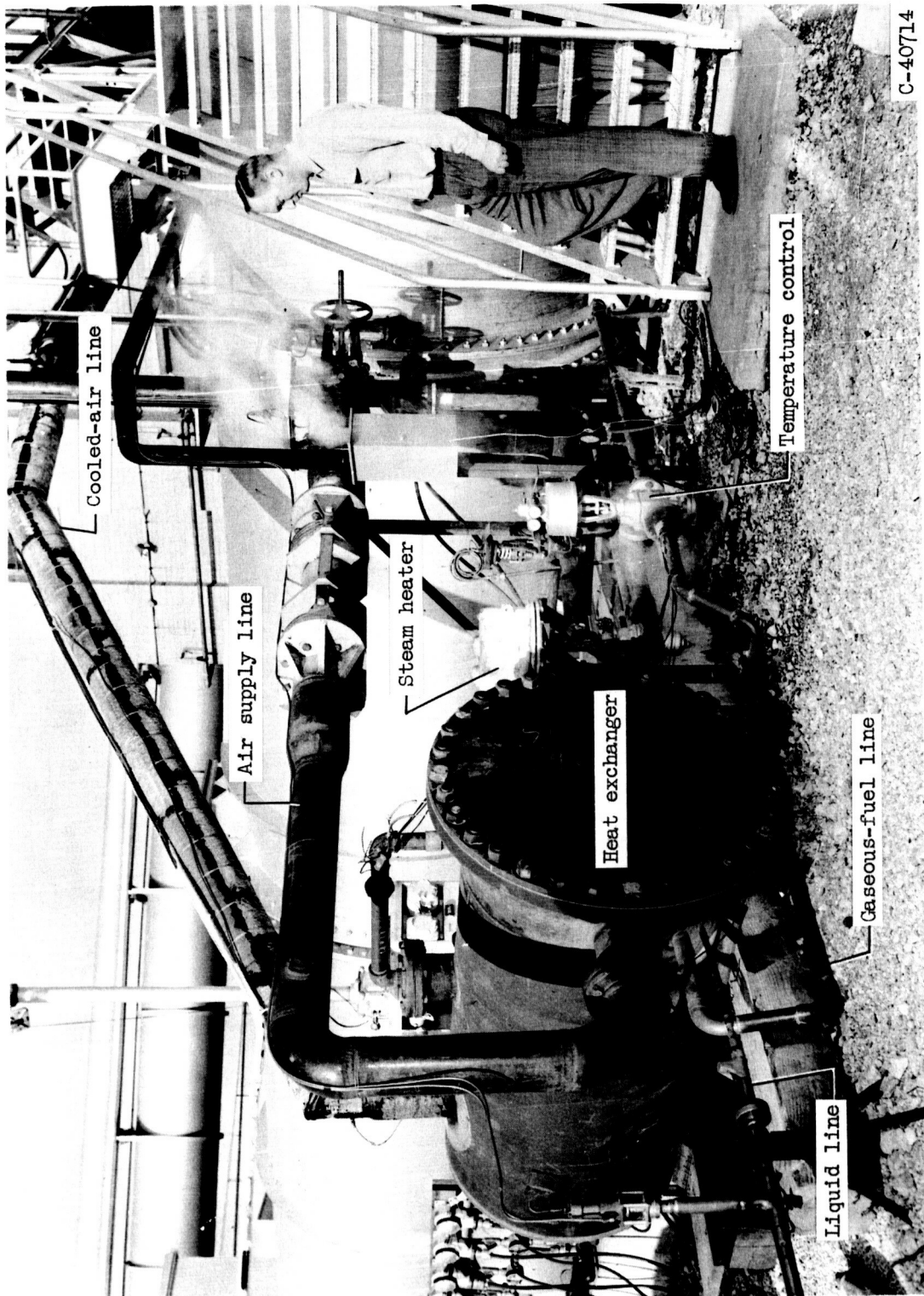


Figure 3. - Heat exchanger.

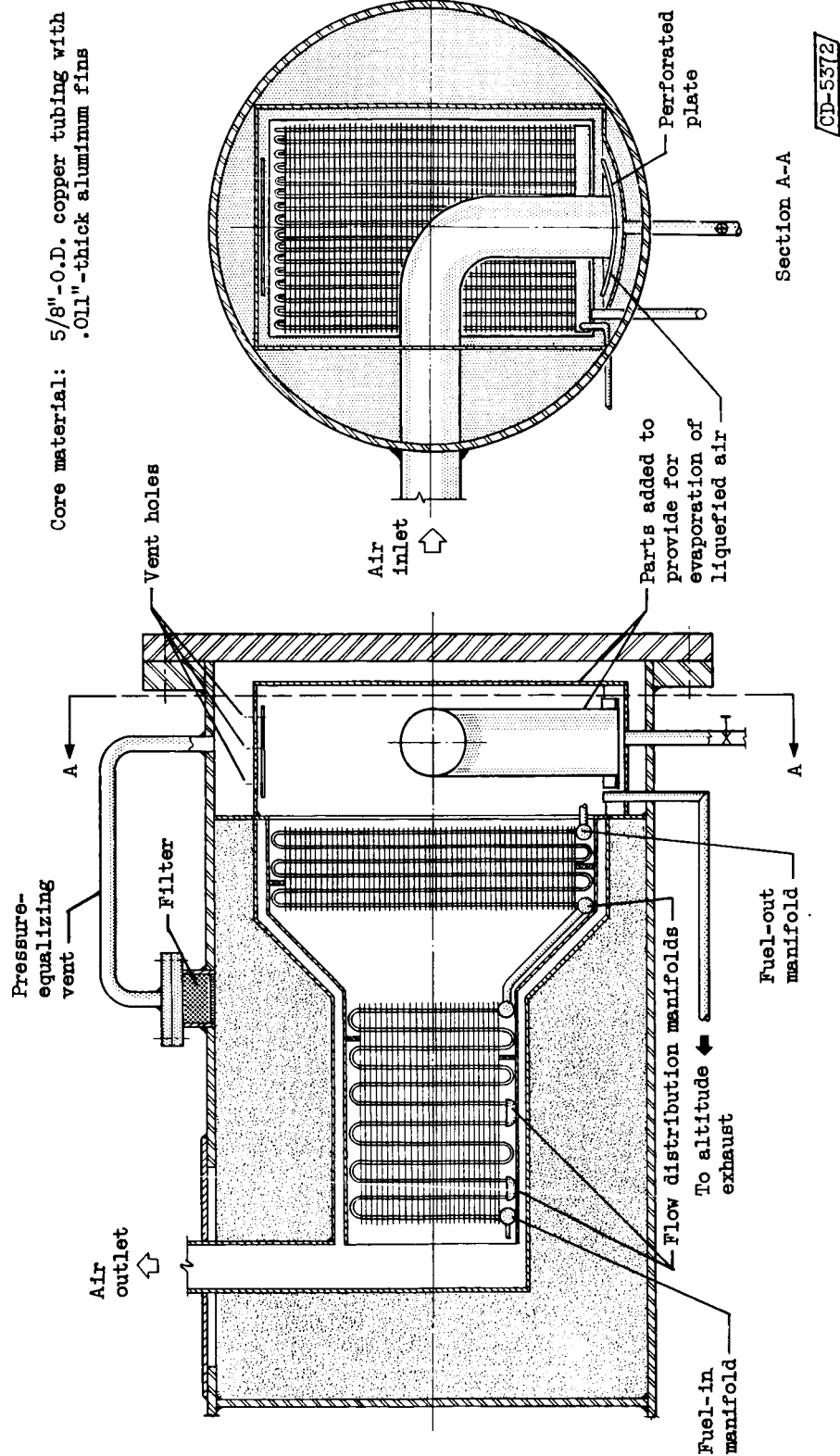
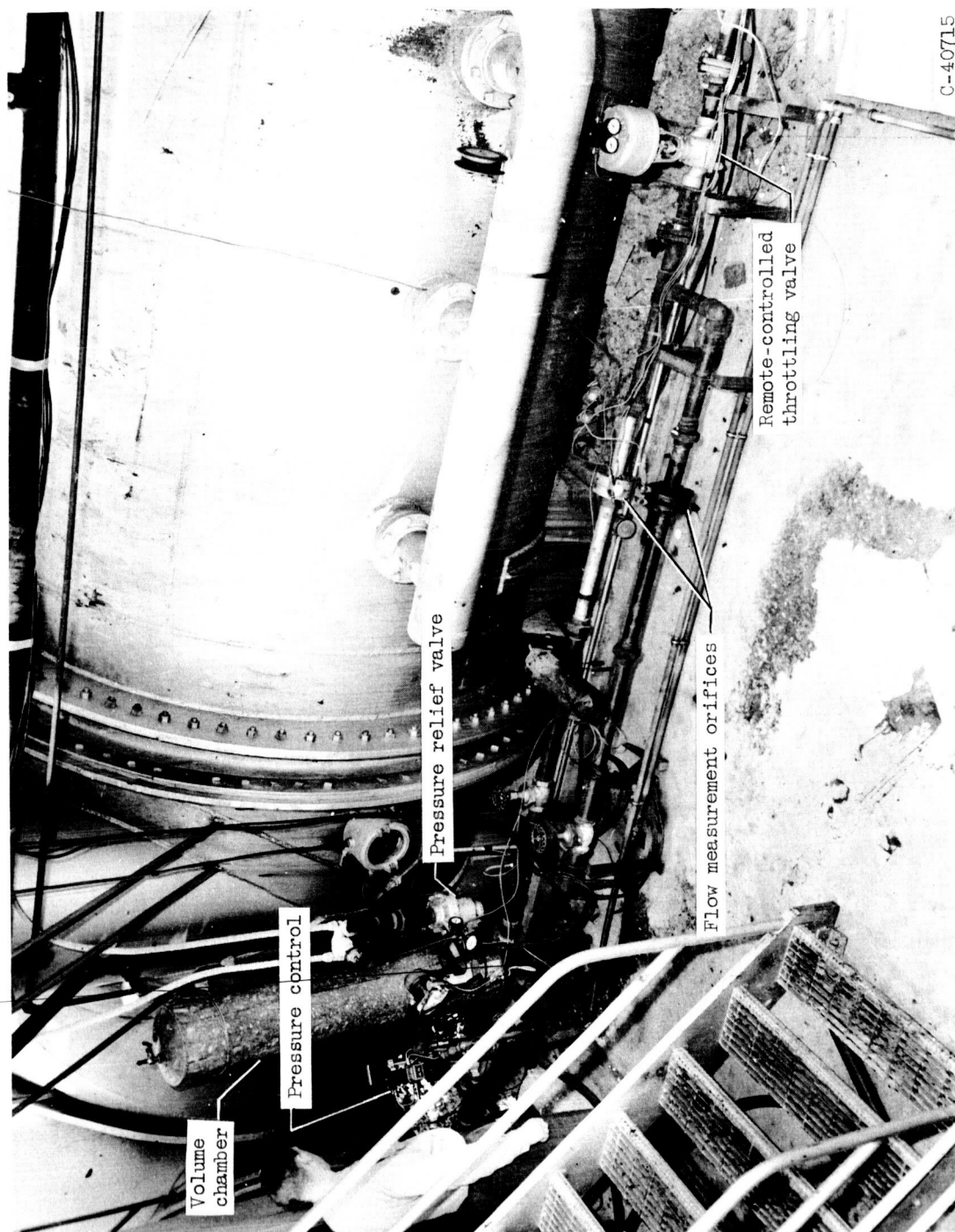


Figure 4. - Cross section of heat exchanger.

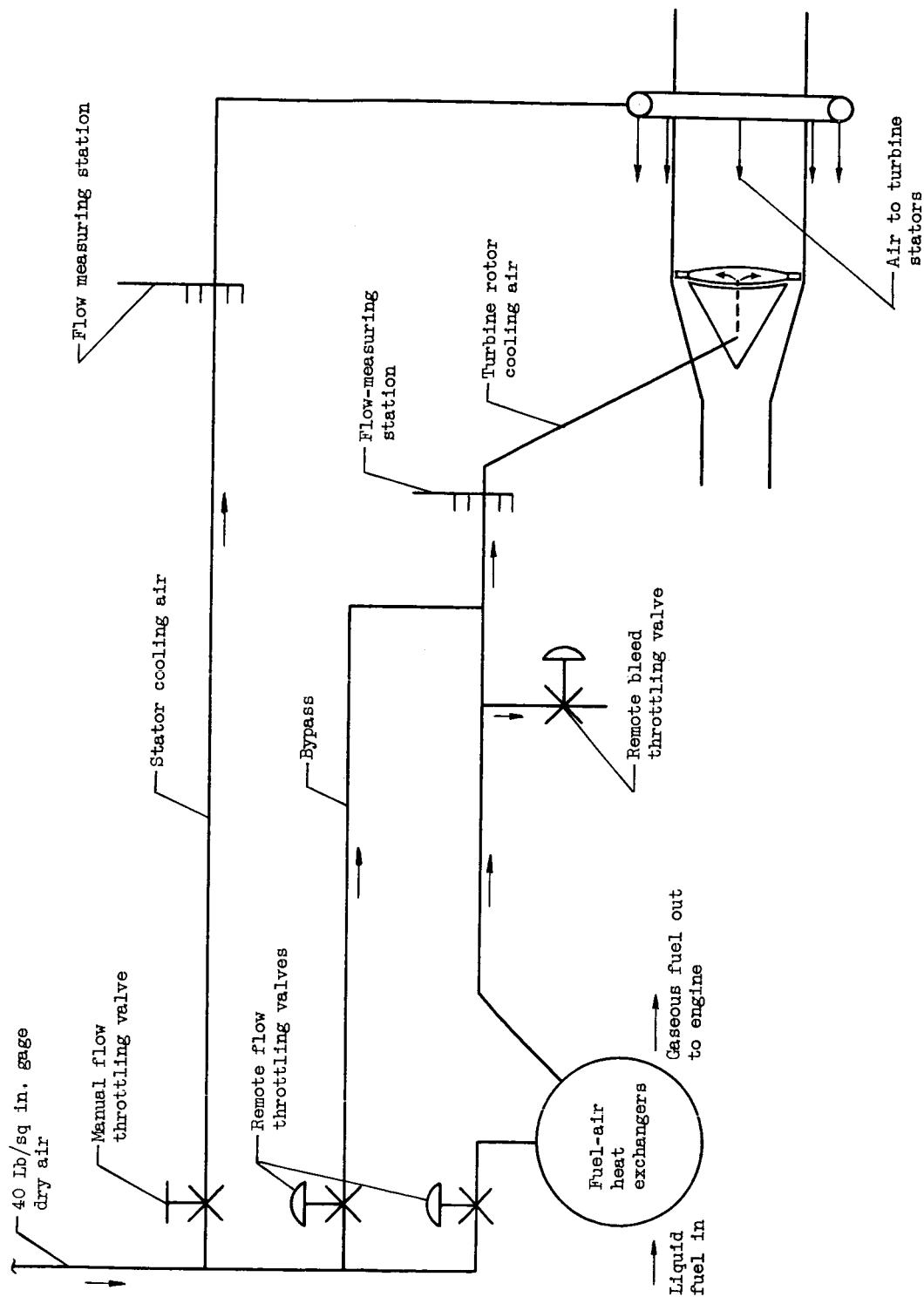
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Figure 5. - Fuel-system controls.

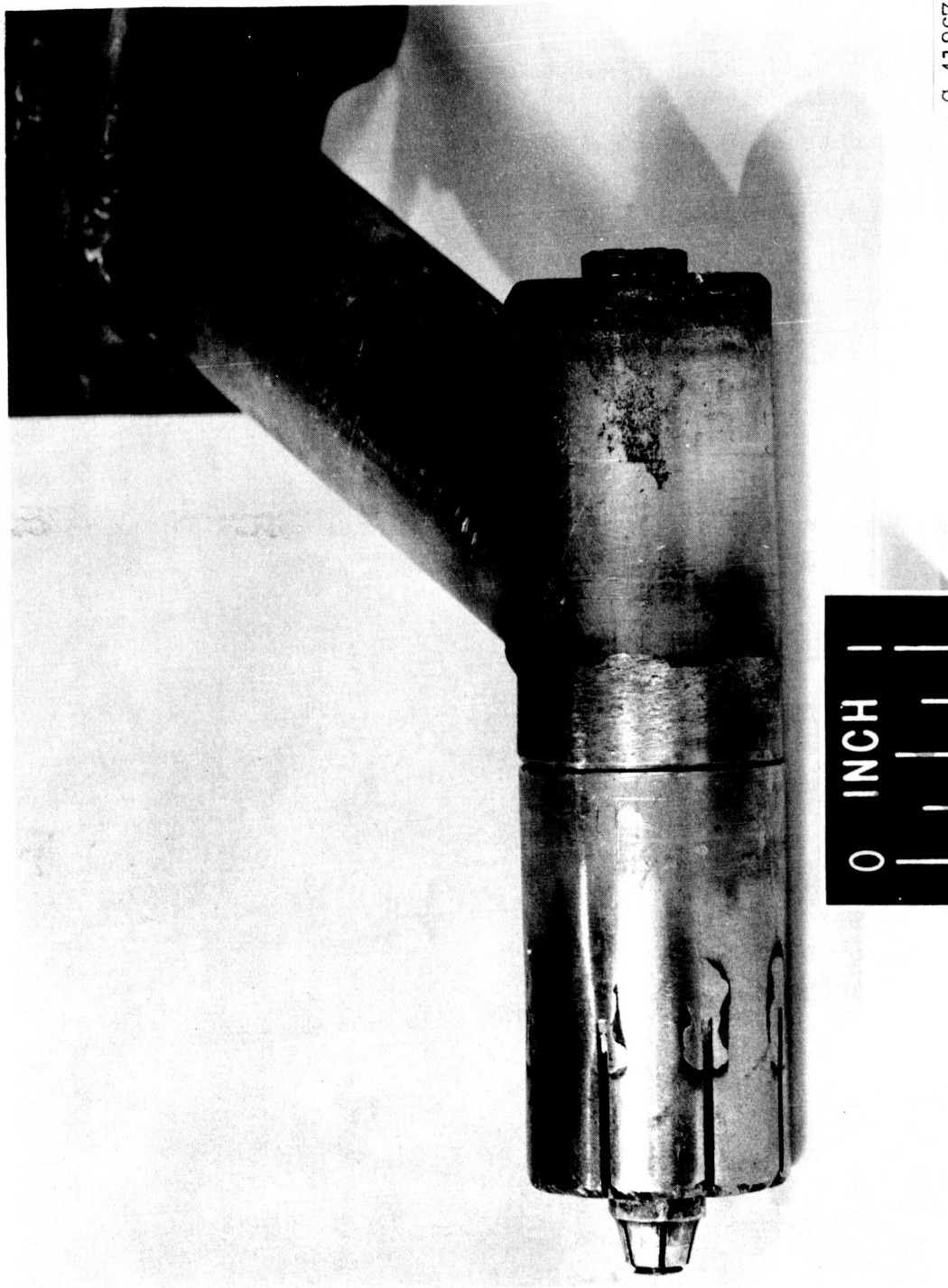
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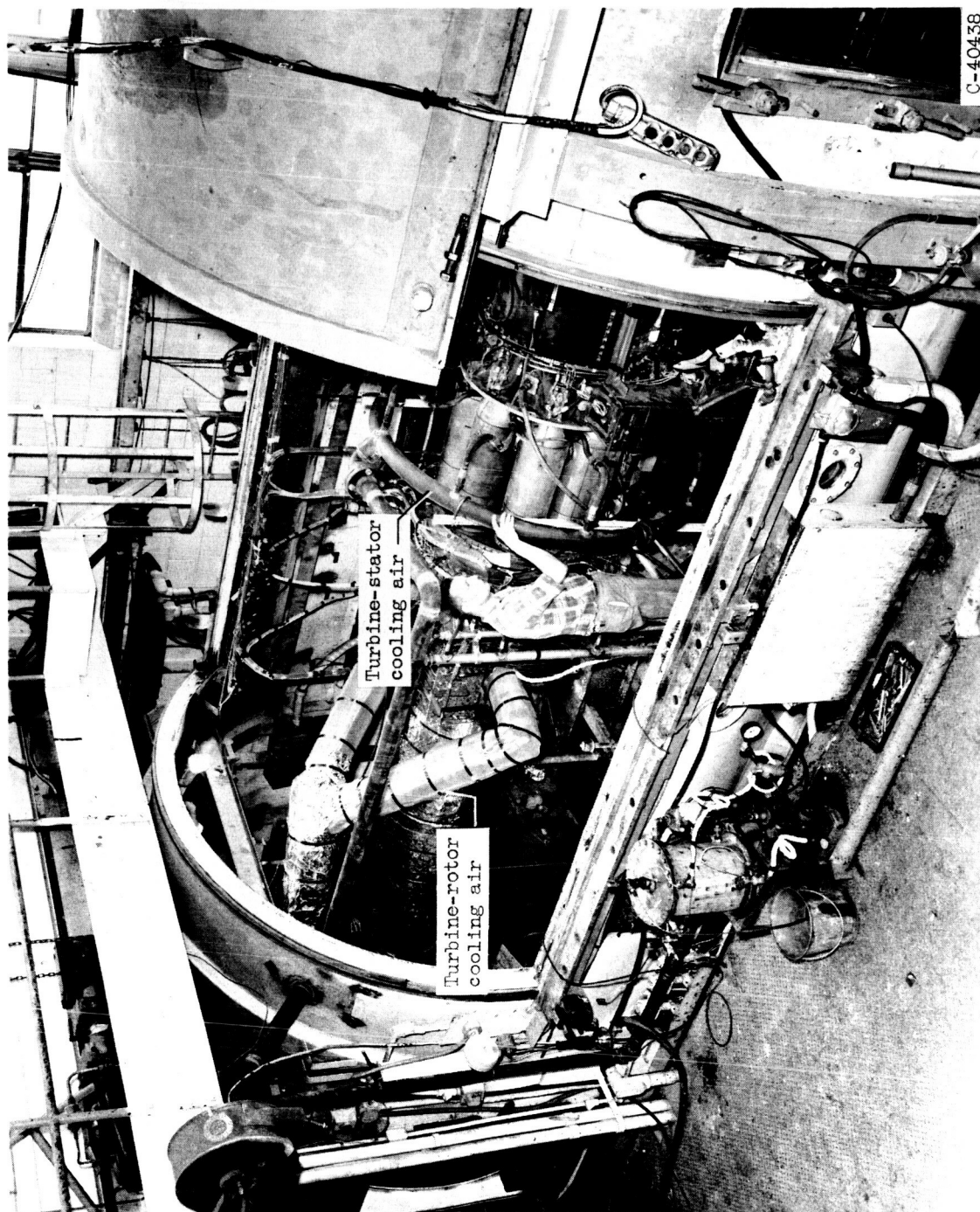
Figure 6. - Turbine cooling-air system.

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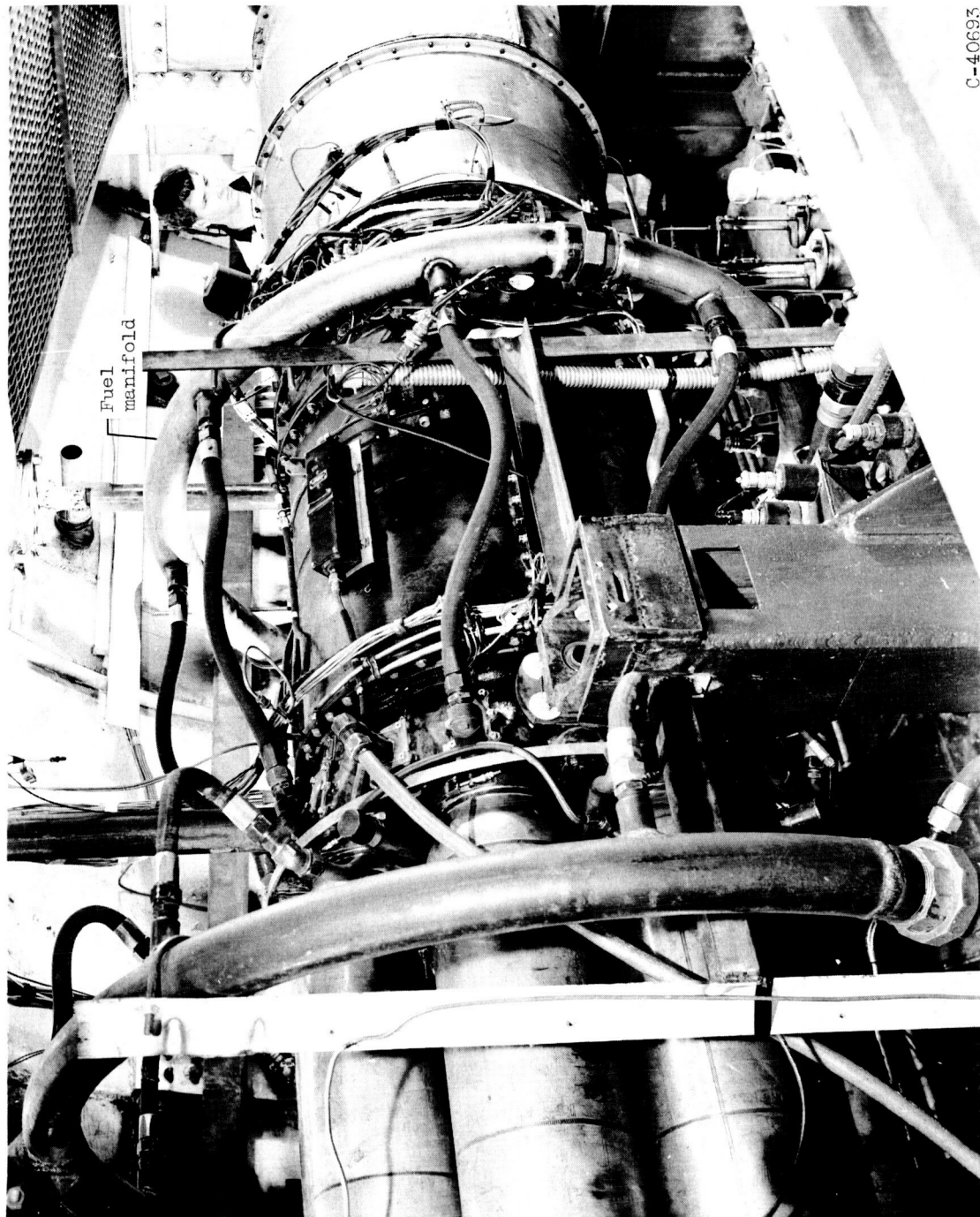
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Figure 7. - Fuel nozzle used in engine.



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Figure 8. - Turbojet engine installed in altitude test chamber.



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Figure 9. - Closeup of engine showing fuel manifold.

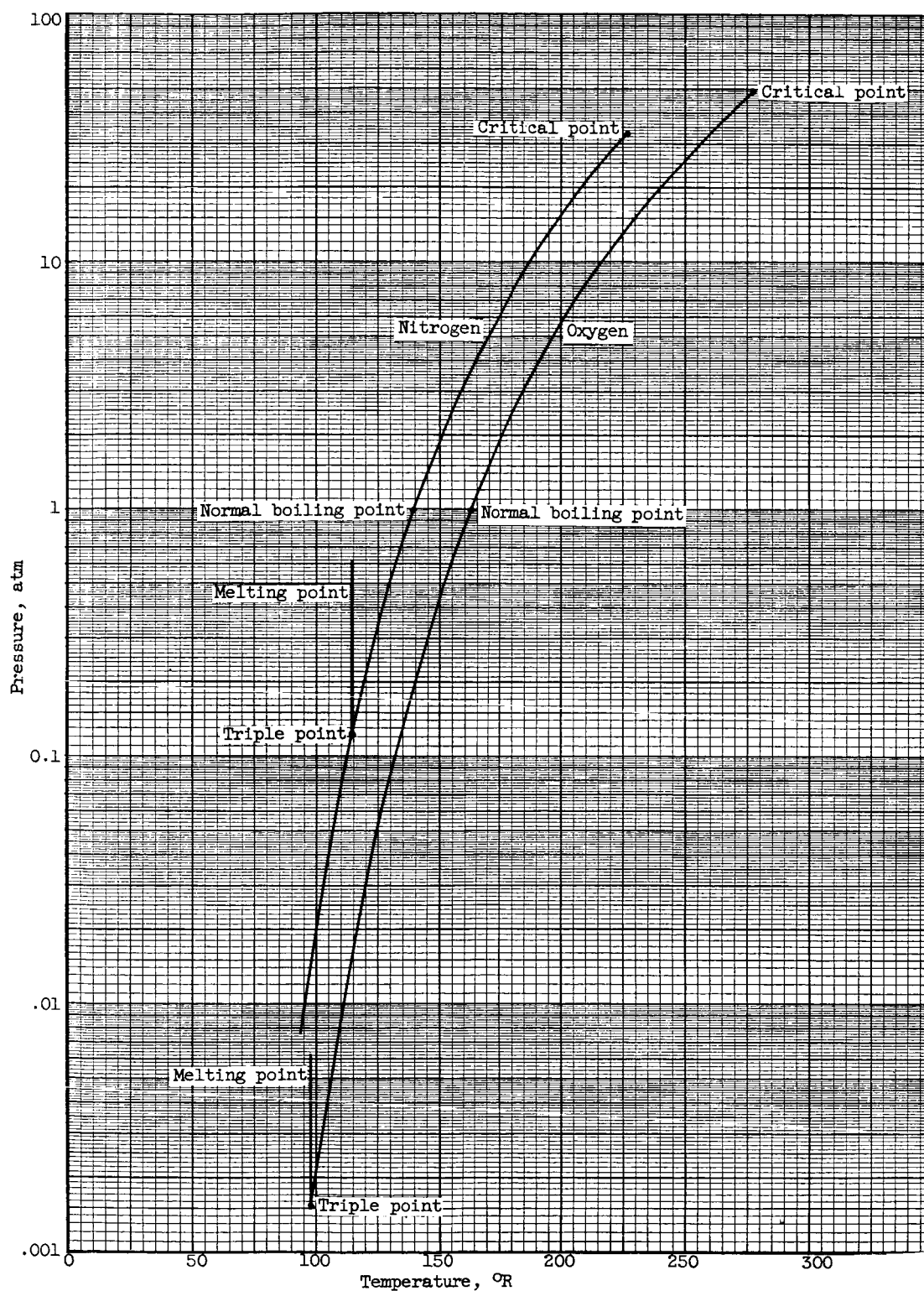


Figure 10. - Relation between temperature and vapor pressure for nitrogen and oxygen.
(Data from ref. 5.)

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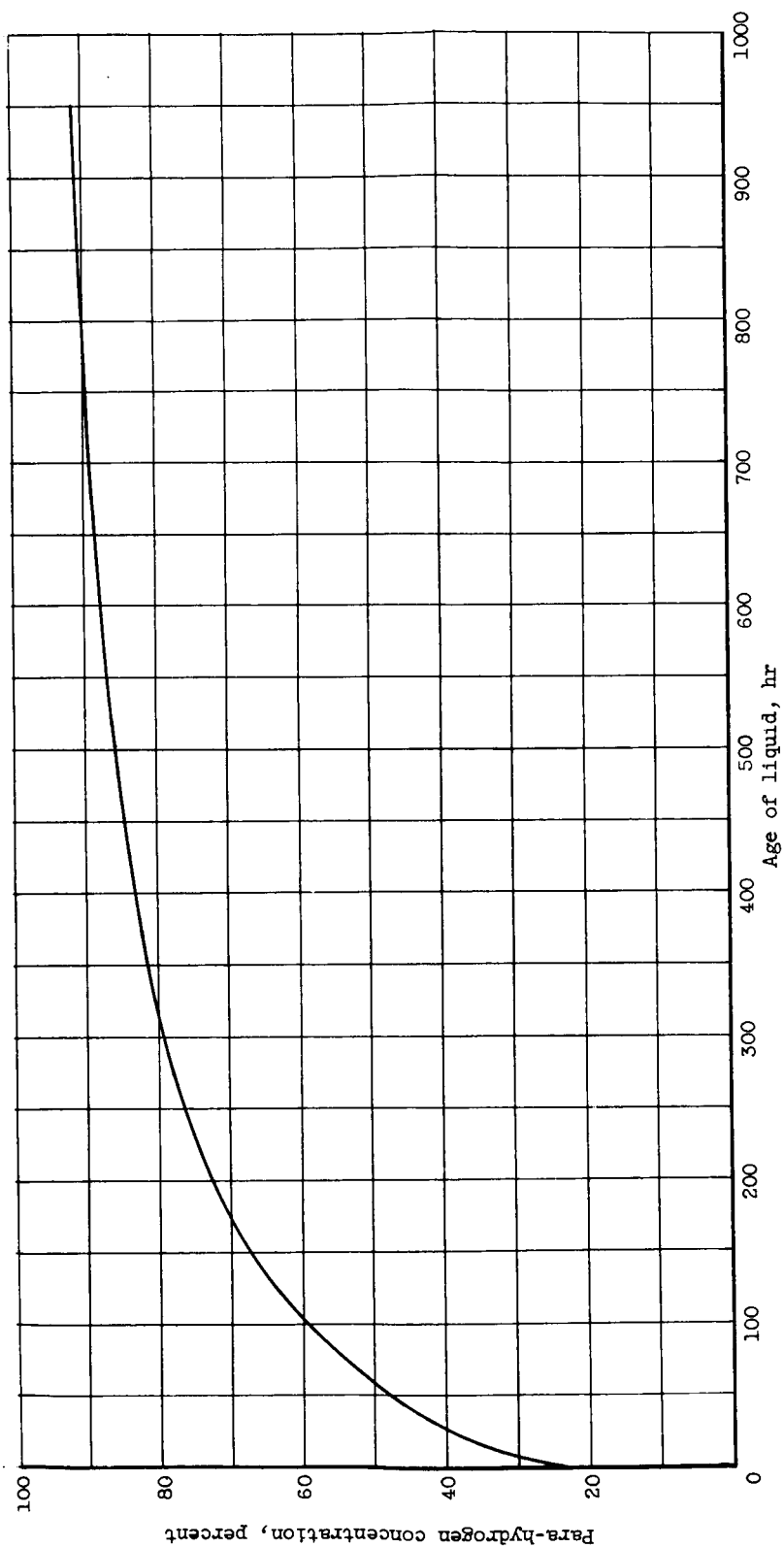


Figure 11. - Rate of conversion of liquid hydrogen during storage. Initial mixture: 25 percent para-hydrogen, 75 percent ortho-hydrogen. (Data from ref. 4.)

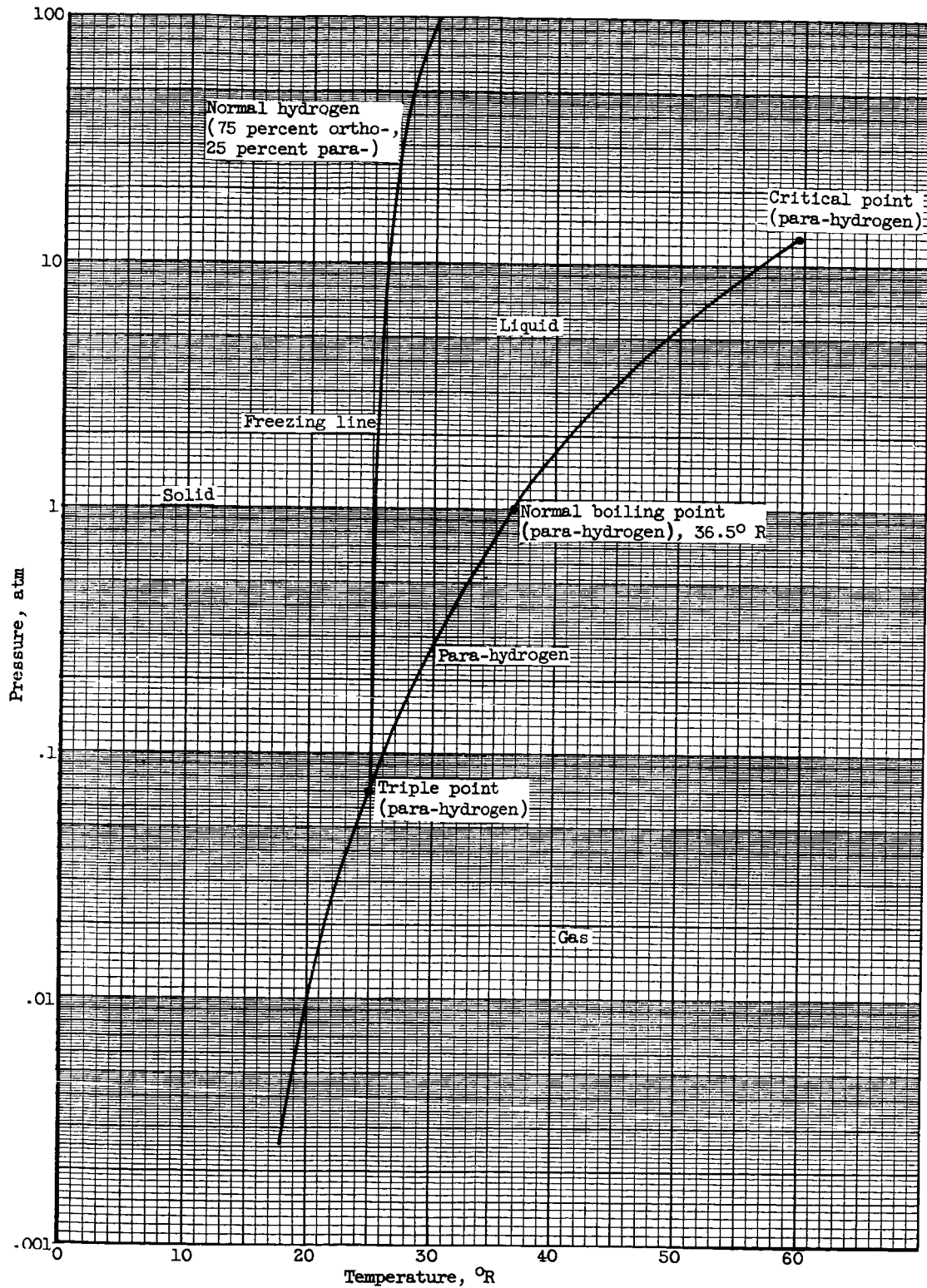


Figure 12. - Relationship between temperature and vapor pressure for hydrogen. (Data from ref. 5.)

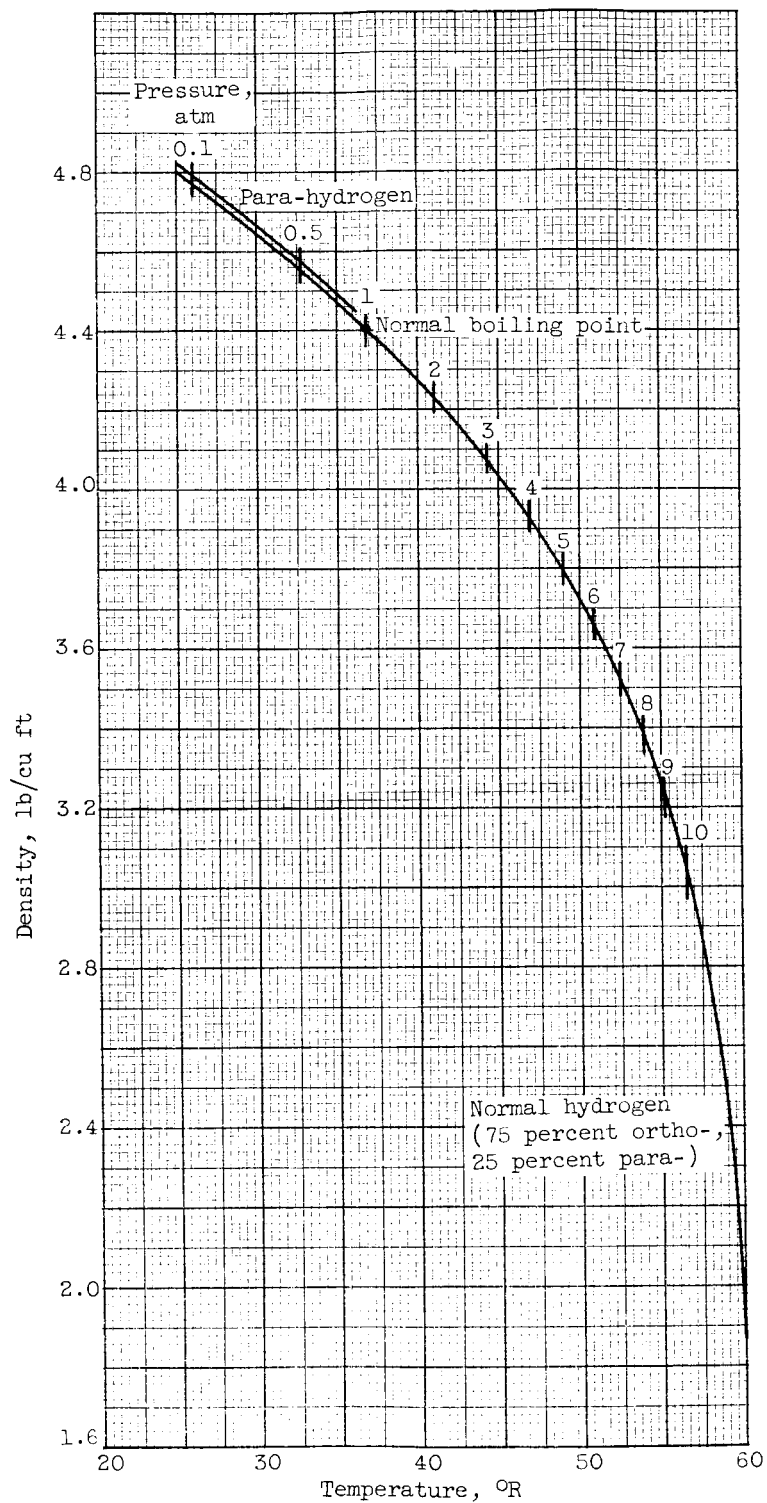


Figure 13. - Density of liquid hydrogen as function of temperature at saturation pressure. (Data from ref. 4.)

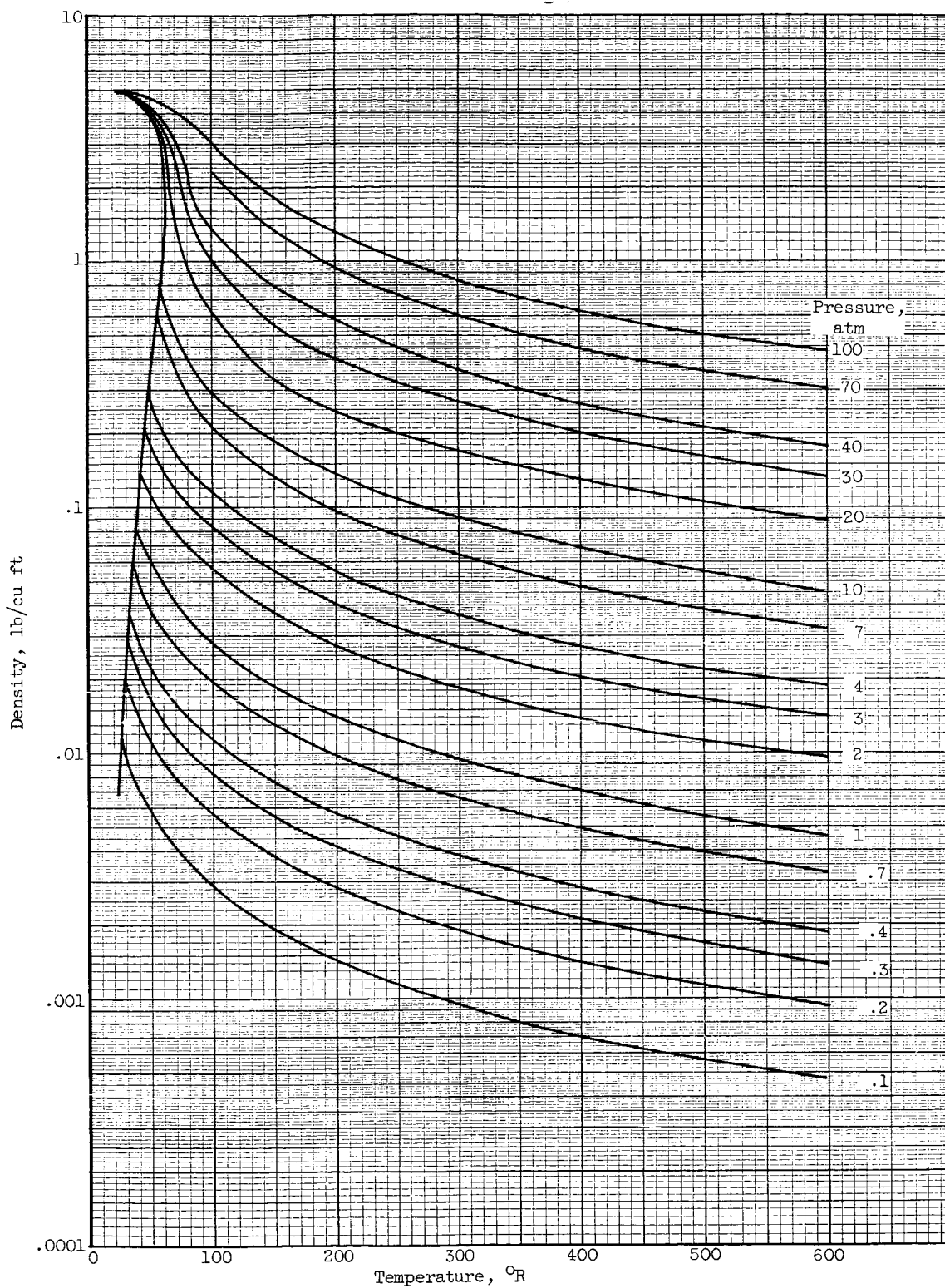


Figure 14. - Density of normal hydrogen gas (75 percent ortho-, 25 percent para-) as function of temperature and pressure. (Data from ref. 4.)

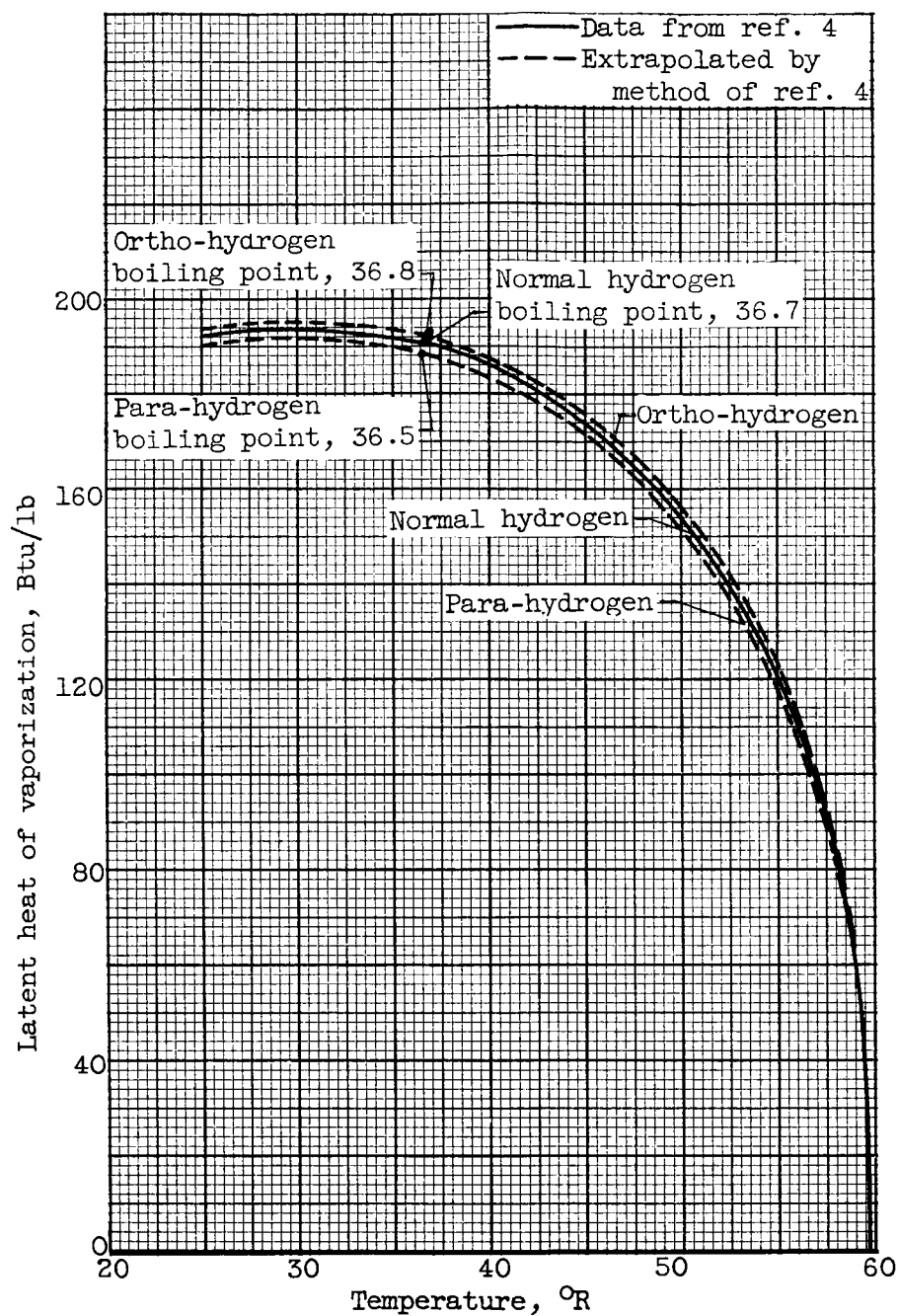
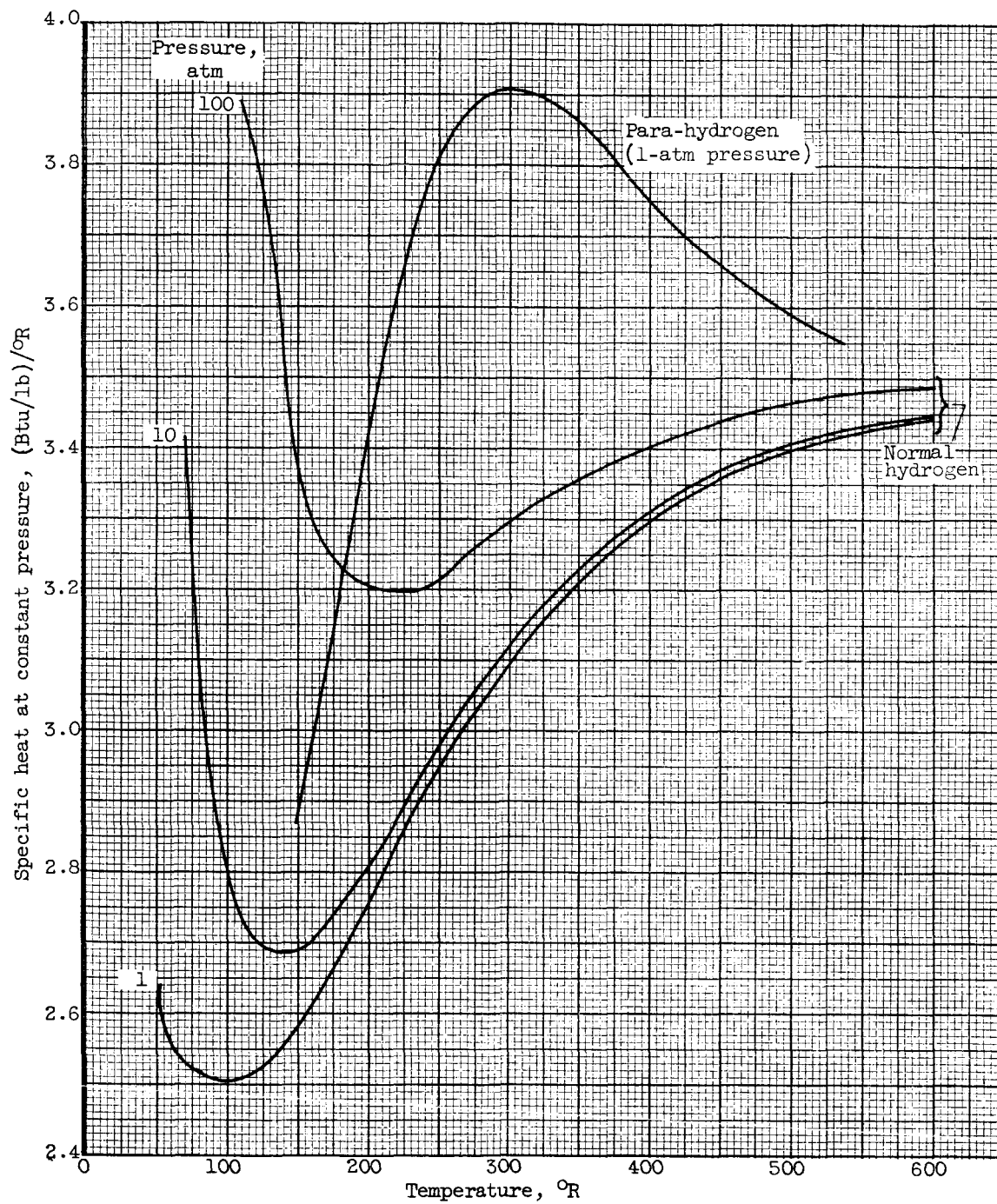
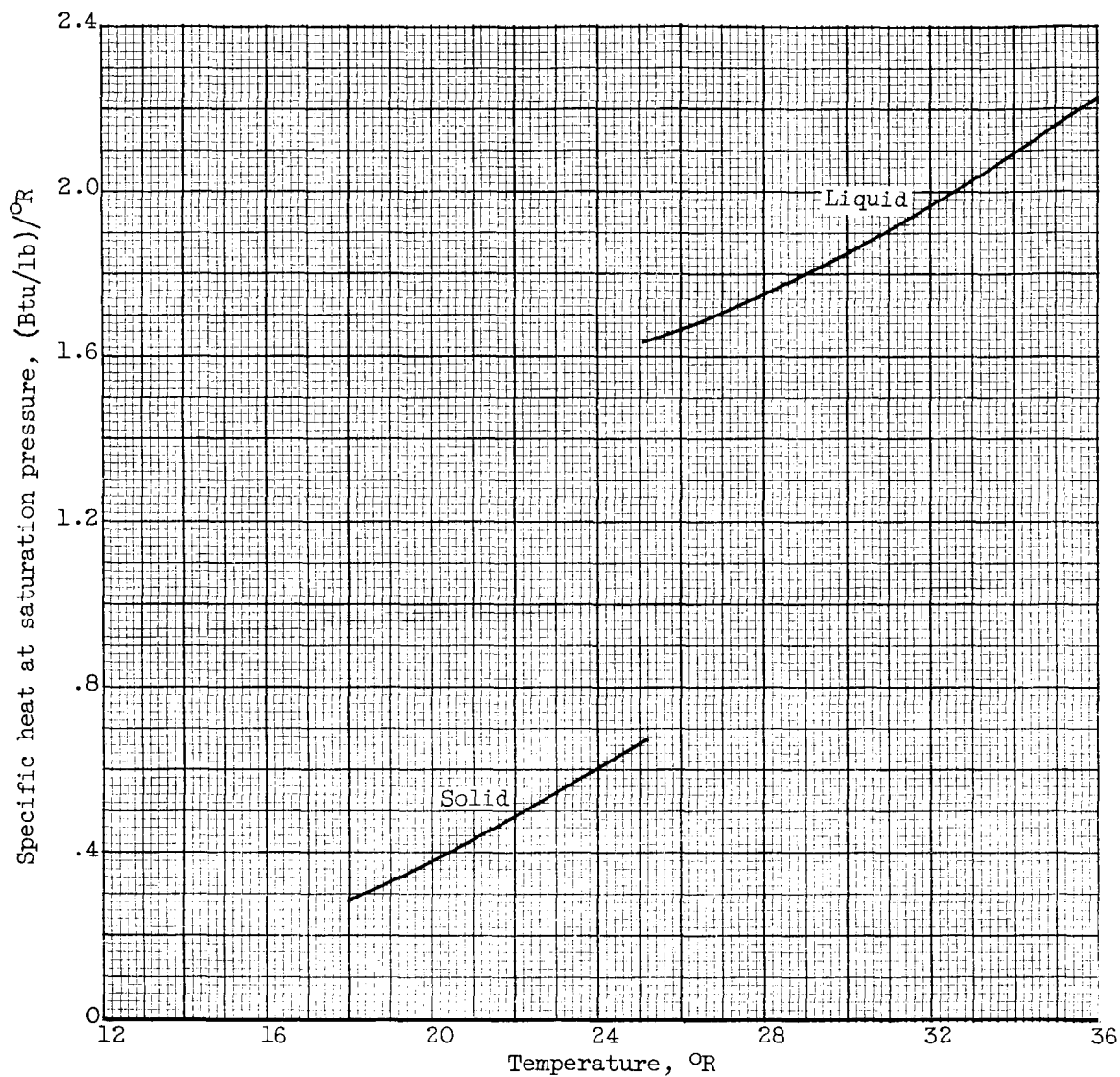


Figure 15. - Latent heat of vaporization of hydrogen as function of temperature for normal, para-, and ortho-hydrogen.



(a) Gaseous hydrogen. (Data from refs. 4 and 5.)

Figure 16. - Specific heat of hydrogen as function of temperature and pressure.



(b) Liquid and solid hydrogen. (Data from ref. 4.)

Figure 16. - Concluded. Specific heat of hydrogen as function of temperature and pressure.

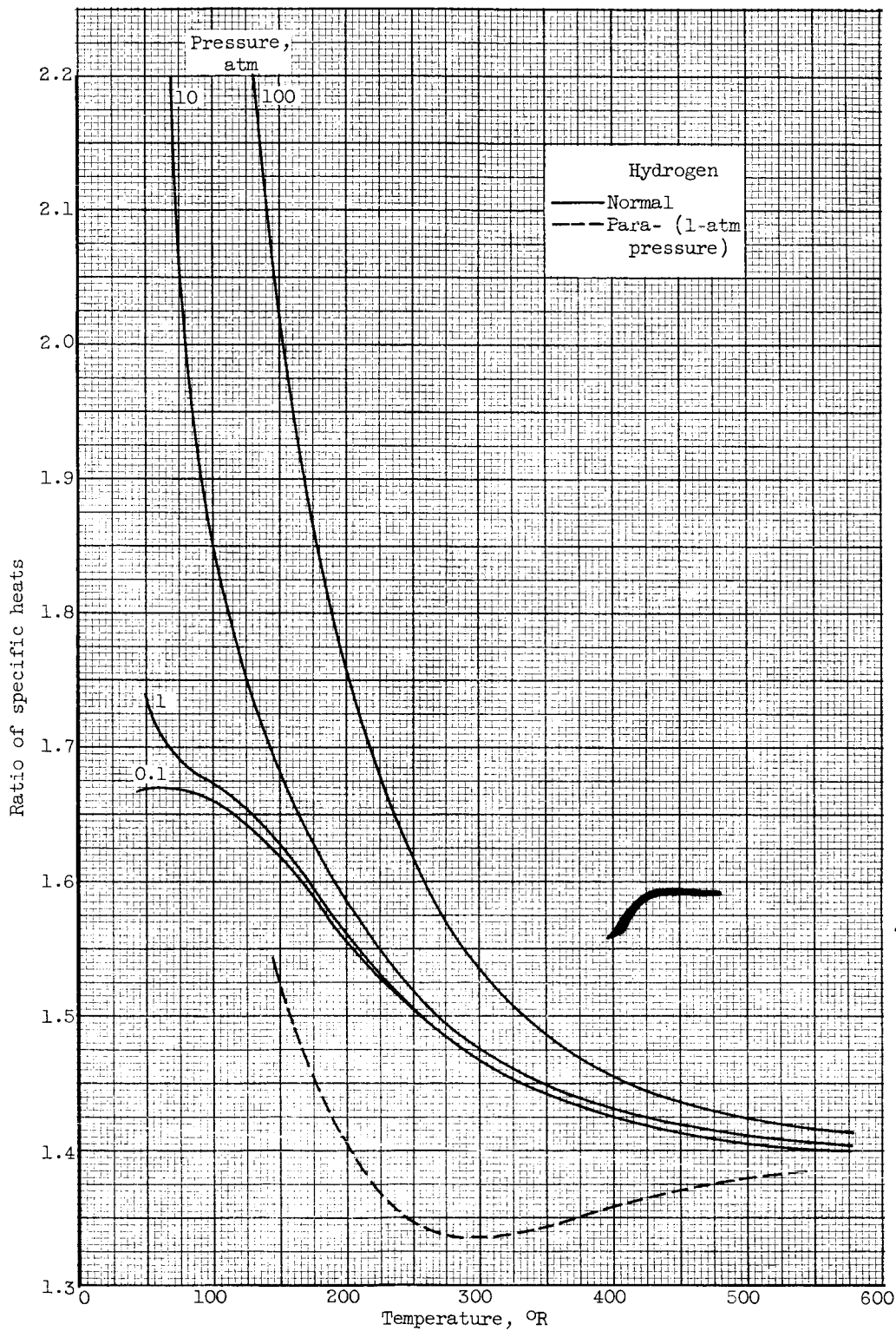
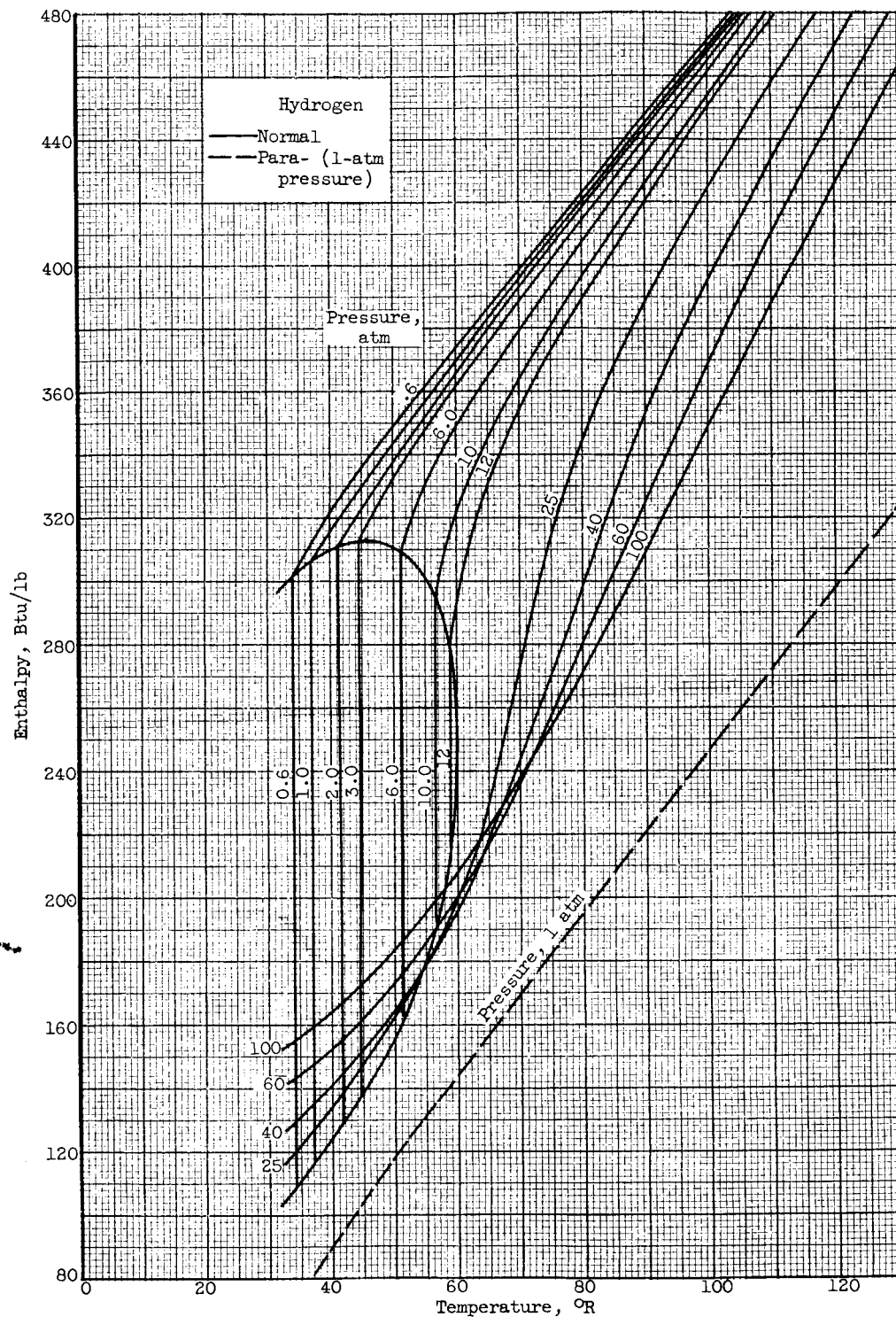
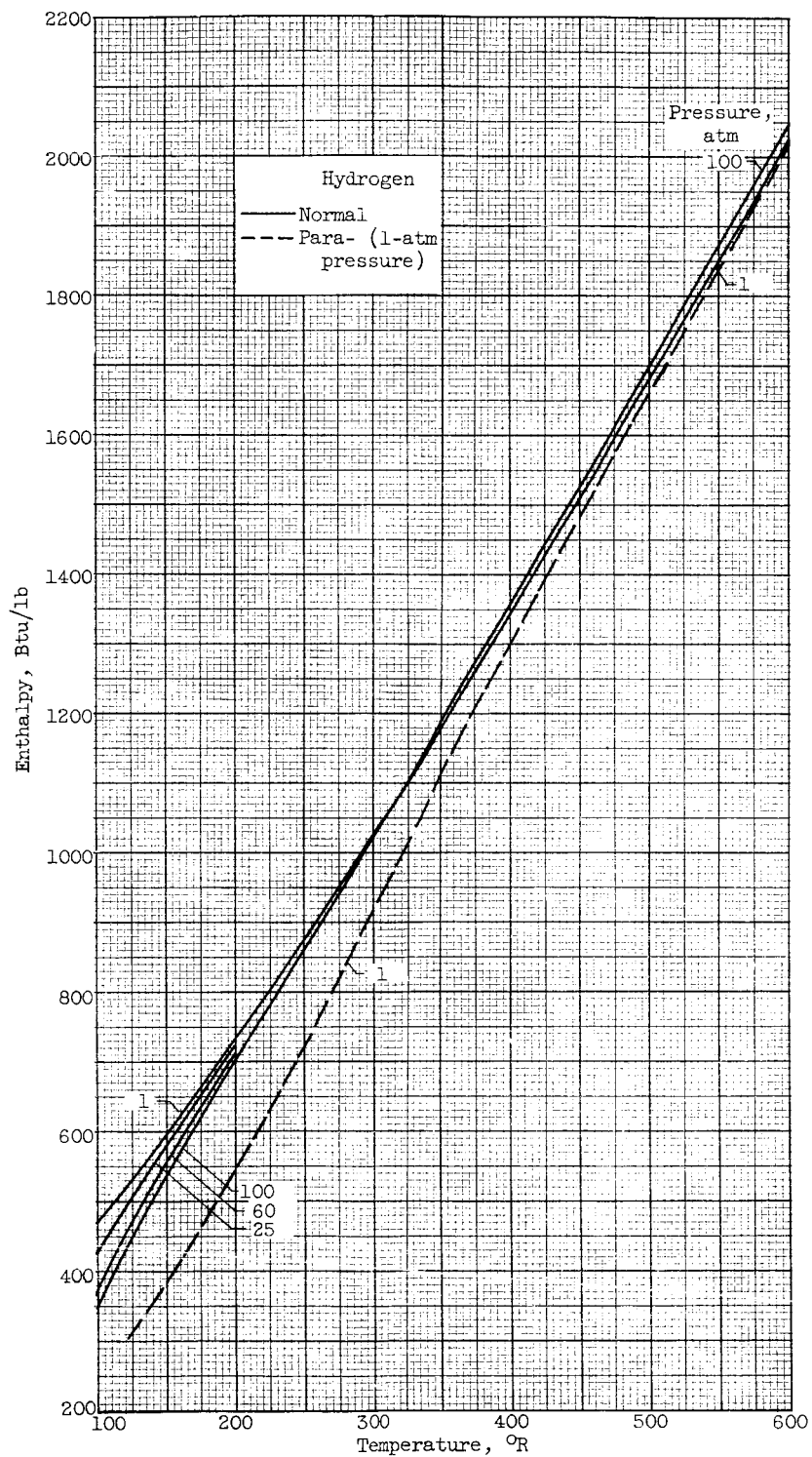


Figure 17. - Ratio of specific heats of hydrogen as function of temperature and pressure. (Information obtained from ref. 5.)



(a) Temperature, 0° to 100° R.

Figure 18. - Enthalpy of hydrogen as function of temperature and pressure. (Calculated from data in ref. 4.)



(b) Temperature, 100° to 600° R.

Figure 18. - Concluded. Enthalpy of hydrogen as function of temperature and pressure. (Calculated from data in ref. 4.)

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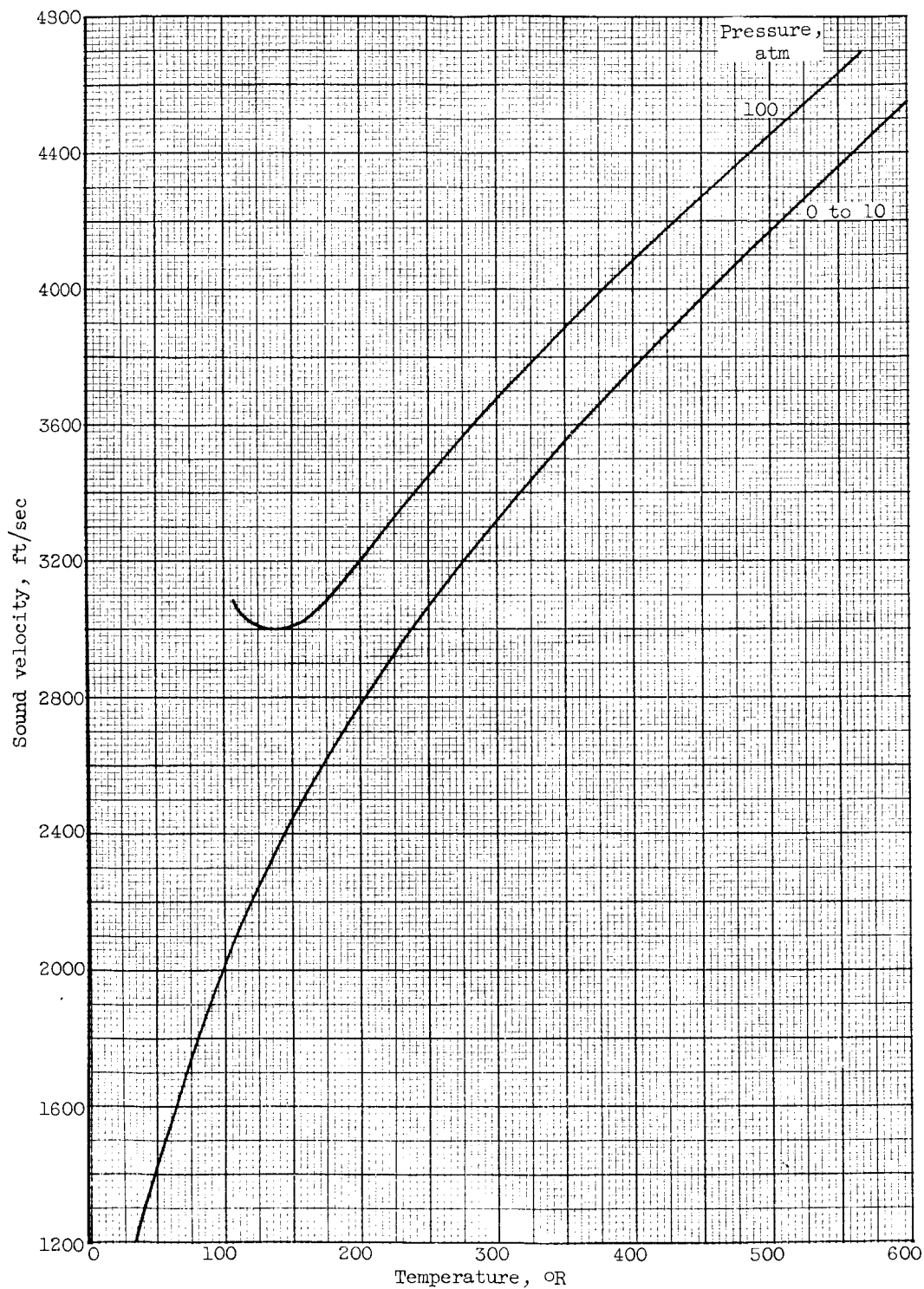


Figure 19. - Sound velocity in normal hydrogen (25 percent para-, 75 percent ortho-) as function of temperature and pressure. (Data from ref. 5.)